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Abstract

This study investigates whether sweep rowers activate their low back muscles asymmetrically when exercising on a rowing ergometer. Given that indoor rowing imposes equal loading demands to left and right back muscles, any side differences in activation are expected to reflect asymmetric adaptations resulting from sweep rowing. In addition to trunk kinematics, surface electromyograms (EMGs) were sampled from multiple skin locations along the lumbar spine of six elite, sweep rowers. The distribution of EMG amplitude along the spine was averaged across strokes and compared between sides. Key results indicate a significant effect of trunk side on EMG amplitude and on the low back region where EMG amplitude was greatest. Such side differences were unlikely because of trunk lateral inclination and rotation, which were smaller than 5° for all rowers tested. Moreover, asymmetries manifested differently between participants; there was not a clear predominance of greater EMG amplitude toward the right/left side in portside/starboard rowers. These results suggest that (a) even during indoor rowing, sweep rowers activate asymmetrically their low back muscles; (b) factors other than rowing side might be associated with low back asymmetries; (c) spatial distribution of surface EMG amplitude is sensitive to bilateral changes in back muscles' activation.

Previous reports have highlighted the markedly high physiological and mechanical demands imposed by competitive rowing (Hase et al., 2002; Volianitis & Secher, 2009). While sports scientists are strongly focused on improving performance, preserving the integrity of ligamentous and musculo-skeletal tissues in rowers' spine remains a key issue. To compensate for the drag forces acting on the shell, and thus to maintain a given average boat velocity, great propulsive forces must act on the blade (Baudouin & Hawkins, 2002). Transmission of force from the foot stretcher to the oar handle, and thus to the blade, imposes however markedly high compression of the spine, especially of the lumbar segments. Estimates of muscle loading in the lumbar spine during a single stroke are 10 times greater (ca. 5000 N; Hase et al., 2002) than the values reported for the external, contact forces measured either in the handle or foot stretcher (400–700 N; Hase et al., 2002; McGregor et al., 2004, 2005). Considering hundreds of strokes are performed during regular training sessions and during competitions, the noticeable loading of back muscles imposed by individual strokes possibly accounts for the frequent occurrences of spine injuries in rowers (Smoljanovic et al., 2009; Hosea & Hannafin, 2012).

In sweep rowing, athletes are split into portside and starboard rowers, according to whether they row with the oar on the left or right boat side, respectively. Considering rowers face the stern of the boat, the blade is, respectively, placed to the right and left side of portside and starboard rowers. Strokes are characterized by trunk lateral rotations toward the rowing side during the recovery phase, when rowers flex their hip, knee, and ankle joints in preparation for the catch, and then to the opposite side during the drive phase, when propulsive forces generated through extension of the lower limbs are transmitted from the foot stretcher to the oarlocks (Smith & Loschner, 2002). The lateral trunk movements, inherent to sweep rowing, may therefore further aggravate the repetitive stress applied to the spine. Numerous studies, indeed, suggest that the asymmetric loading of the spine is a key, potential cause of injuries. A recent descriptive study, for example, observed that changing rowing side was significantly associated with higher incidences of traumatic, low back injuries in sweep rowers (Smoljanovic et al., 2009). Through imaging measurements of the spine, abnormalities were observed in the pars articularis at L5 level in six out of nine rowers. Five of these stress reactions were unilateral, with side of stress being not correlated with rowing side (Maurer et al., 2011). Moreover, disproportionate flexibility of left and right hamstring muscles, rather than general flexibility, was associated with low back pain (Stutchfield & Coleman, 2006). Lateral damage has also been observed at trunk thoracic segments, with rib stress fractures occurring at either trunk side in both sweep rowers and scullers (Christiansen & Kanstrup, 1997). Notwithstanding the documented

evidence on the asymmetrical development of spine injuries in sweep rowers, little is known about the side differences in the activation of back muscles during rowing. Previous electromyographic studies on rowers were chiefly focused on the timing of proximo-distal activation of back muscles (Roy et al., 1990; Parkin et al., 2001; Caldwell et al., 2003; Pollock et al., 2009; Turpin et al., 2011). Some studies have investigated left and right differences in erector spinae activation while oarsmen were engaged in isometric contractions, not during rowing (Roy et al., 1990; Parkin et al., 2001). To our knowledge, previous accounts were not specifically focused on asymmetries in back muscle activation during rowing.

During on-water rowing, asymmetric activation of the back muscles may have two origins. On one hand, the uneven loading of back muscles may be a consequence of lateral trunk movements associated with sweep rowing. On the other hand, rowers may rely on the differential activation of left and right back muscles to control boat stability, especially during the recovery phase (i.e., when rowers strive to balance the boat without support from the blades). Therefore, in an attempt to control for the effect of trunk lateral rotations and boat stabilization on the bilateral pattern of activation of the back muscles in sweep rowers, it seems relevant to understand how the nervous system modulates activity in the back muscles during indoor rowing.

In this study, from surface electromyograms (EMGs), we investigate whether elite athletes activate their back muscles symmetrically during indoor rowing. In such a dynamic condition, changes in the amplitude of surface EMGs may not reflect changes in activation; EMG amplitude is strongly affected by the relative movements between muscles and skin (Farina et al., 2003). With a large array of electrodes, we circumvent this limitation and ask: does the spatial distribution of amplitude of surface EMGs recorded from left and right back sides change equally throughout individual strokes? If uneven loading of back muscles is exclusively associated with boat stabilization demands, then, during indoor rowing, we expect EMG amplitude to vary similarly at both trunk sides of healthy, elite athletes.

Methods

Subjects and experimental protocol

A convenience sample of six elite rowers (1 female; mean ± SD; age: 22 ± 6 years; height: 179 ± 6 cm; body mass: 70 ± 4 kg) was recruited to participate in this experiment, after providing written, informed consent. All participants were gold medalists in national rowing competitions and rowed from 3 to 12 years. Two athletes were awarded the gold medal in the World Rowing Championships held in 2005 and 2006 (subject 4; coxless two and eight, respectively; 12 years of rowing) and in 2012 (subject 1; coxless four; 3 years of rowing). The female rower was awarded the gold medal in the latest European Rowing Championship (coxless four). Two participants were starboard rowers and one participant has not trained on sculling boats since he started rowing. Except for the female rower, all athletes were right-handed. Four participants were collegiate rowers and the other two rowers had no occupation outside their sporting profession. All athletes were not active in sports imposing unilateral activation of the trunk muscles (e.g., tennis or jumping events) and did not report any significant injuries in the lower limb or spine that could potentially lead to asymmetries. Low back pain occurrences were however reported by all participants at least once during rowing activities, with pain intensity ranging from 6% to 86% (visual analog scale). Experiments conformed to the latest revision of the Declaration of Helsinki and were approved by the Institutional Ethics Committee.

Before starting data collection, a 5-min warm-up session was applied. During warm-up, subjects rowed on an indoor rowing machine (Concept II Model E, Morrisville, North Carolina, USA) as if preparing themselves to engage in a regular training session. After warm-up, a series of 30 consecutive strokes were performed at three rowing cadences: 18, 24, and 32 strokes/min. These trials were applied at random order, with intervals between consecutive trials ranging from 2 to 5 min. Instantaneous, visual feedback of the stroke rate was provided to subjects through the rowing machine display. Subjects were allowed to practice while

wearing sensors used to collect muscle activity and trunk kinematics data; none of them reported discomfort or difficulty to row during experiments. Participants were asked to adjust the resistance of the rowing machine at their preferred level while keeping their average pace from 115 to 120 s, from 105 to 110 s, and from 95 to 100 s every 500 m, respectively, for 18, 24, and 32 strokes/s. For the female rower, these respective figures were 135–140 s, 125–130 s, and 115–120 s every 500 m. The same resistance was then considered for the three cadences.

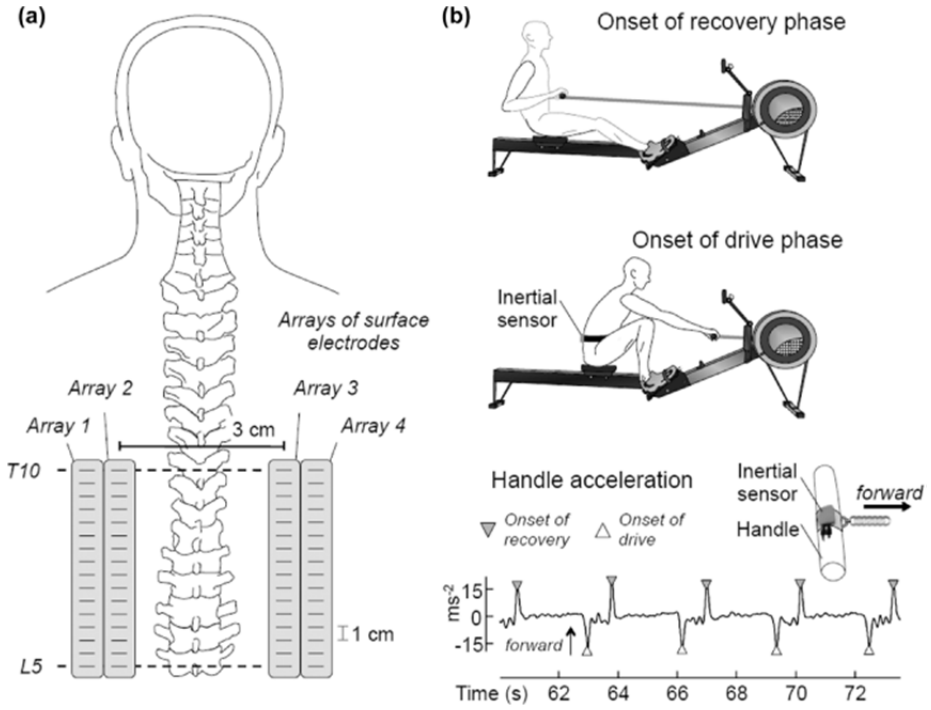
Considering electrode position may account for changes in the amplitude distribution of surface EMGs collected from the back muscles (Farina et al., 2003), especially in dynamic conditions such as rowing, a repeatability study was conducted on an additional group of three portside rowers (age: 27, 27, and 33 years). These participants have been engaged in competitions at international levels until they, respectively, reached 24, 25, and 25 years; currently, they train 5 days per week. After warm-up, each subject performed a series of 30 strokes at a rate of 24 strokes/min, before and after electrode repositioning. As for the sample of elite rowers, these participants were asked to keep an average pace of 105–110 s/500 m.

EMG recordings and electrode positioning

Monopolar surface EMGs were recorded with four arrays of 16 silver bar electrodes each (semi-disposable adhesive arrays; electrode size: 1 × 10 mm; inter-electrode distance: 10 mm; Spes Medica, Battipaglia, Italy). Electrode-skin contact was ensured by filling electrode cavities with conductive paste (TEN 20 Conductive Paste, Weaver, Aurora, Colorado, USA). EMGs were amplified by a variable factor across subjects (200–1000) to maximize signal-to-noise ratio while not resulting in saturation (10–750 Hz EMG-USB amplifier, LISiN and OT Bioelettronica, Turin, Italy). Then, EMGs were digitized at 2048 samples/s (12 bits A/D converter) and stored for analysis (OT Biolab, OT Bioelettronica).

After abrading and cleaning the skin with alcohol and an abrasive paste, each electrode array was carefully positioned on the back muscles; two arrays were positioned on the left and two on the right, trunk side. Specifically, the midline of the most medial array was located 1.5 cm laterally to the vertebral, spinous process and roughly spanned skin regions from L5 to T10. Lateral arrays (arrays 1 and 4) were positioned alongside medial arrays (arrays 2 and 3; Fig. 1(a)). The procedure we considered for the positioning of surface electrodes was sought to cover most of, if not entirely, the medial and lateral portions of the lumbar, erector spinae (Daggfeldt et al., 2000) and multifidus (Rosatelli et al., 2008) muscles. Furthermore, by covering a somewhat large skin region with arrays of electrodes, we expected to minimize the sensitivity of surface EMGs to variations in the relative position between the erector spinae muscle and electrodes (Farina et al., 2003; DeNooij et al., 2009).

Figure 1.



Electrode positioning and identification of individual rowing cycles. Panel (a) shows the position of electrodes in relation to the spine (figure not in scale). L5 location was identified through palpation and marked on the skin. Two pairs of arrays of 16 surface electrodes were positioned one on each side of the spine. The most medial arrays (number 2 and 3) were positioned 1.5 cm laterally to the spine midline, whereas the most lateral arrays were located alongside them. The most caudal row of electrodes coincided with the transverse location of L5 spinous process. Arrays were aligned parallel to the line connecting the spinous process of this and the seventh cervical vertebra. Spinous processes of both vertebrae were identified with the subject in prone position. Panel (b) schematically shows the body postures at the onset of the rowing recovery (top) and drive (middle) phases. These instants were identified from acceleration data, measured through an inertial sensor firmly secured to the handle of the rowing machine (bottom panel shows acceleration data for a single subject performing at 18 strokes/min). Onsets of recovery and drive phases corresponded to positive and negative peaks in handle acceleration, respectively. The direction and amplitude of trunk movements were quantified through an inertial sensor secured in correspondence of L3.

The same experimenter (N. G. R.) was fully responsible for the positioning of electrode arrays for all participants. Electrodes were positioned while subjects were lying in prone position on a padded bed. Specifically, in relation to the three rowers recruited to participate in the repeatability analysis, only the right side of the lumbar spine (cf. arrays 3 and 4 in Fig. 1) was considered for electrode positioning and repositioning. Immediately after the first series of 30 strokes, arrays were removed and the prints left by the conductive paste on the skin were completely cleaned. After 20 min of rest, the experimenter repositioned the arrays and the series of 30 strokes started over.

Kinematics and ultrasound measurements

Inertial sensors (MTx, XSens, Enschede, the Netherlands) were used to quantify kinematic changes during and across rowing cycles. Specifically, one sensor was tightly fixed to the handle of the rowing machine; handle acceleration was recorded and considered to identify instants denoting the start and end of individual cycles. Another sensor was secured to the spine lumbar segment with a large (10 cm), elasticized Velcro strap, in correspondence of L3 (Fig. 1(b)). In this region, the inertial sensor seems less influenced by movements of the pelvis (Meichtry et al., 2007). From the data provided by this sensor, we were able to quantify inclinations of the lumbar spine in each of the three anatomical planes during rowing. Data corresponding to handle acceleration and trunk inclination were both sampled at 100 samples/s (12 bits A/D converter). EMGs and kinematics data were offline synchronized through a common trigger.

Side differences in the amplitude of EMGs could result from side differences of anatomical rather than neural origin (e.g., differences in subcutaneous thickness; Farina et al., 2002). For this reason, we measured the thickness of the subcutaneous tissue covering the erector spinae muscle. Ultrasound images of back muscles and subcutaneous tissues were collected with a linear probe (7 MHz, 59 mm field of view, LogicScan 128, Telemed, Vilnius, Lithuania), placed parallel and 2.5 cm laterally to the spine midline. The central location of our ultrasound transducer coincided with the skin region corresponding to the center of each pair of electrode arrays, both in the transverse and longitudinal directions. This positioning provided us with a representative view of the subcutaneous tissue interposed between electrodes and muscles. We thus quantified the subcutaneous thickness by considering the distance from the outer layer of the lumbodorsal fascia to the skin-fat interface in the ultrasound images.

Data analysis

Individual rowing cycles were identified from peaks in the handle acceleration data. Instants of positive and negative acceleration peaks, which correspond to zero crossings in handle velocity (Hase et al., 2002), were associated with the onset of the recovery phase and to the onset of the catch phase, respectively (Fig. 1(b)). These peaks were automatically identified through a custom written Matlab script (The MathWorks Inc., Natick, Massachusetts, USA). Once onsets were identified, the duration of both recovery and catch phases was computed for each of the three rowing cadences. Onsets were further used to decompose data related to the muscle activation and to the trunk inclination in the three anatomical planes, according to individual rowing cycles.

Variations in the activation of back muscles during indoor rowing were estimated from the root mean square (RMS) amplitude of surface EMGs, separately for each trunk side. Initially, we computed the algebraic difference between monopolar EMGs collected from consecutive pairs of electrodes in the longitudinal direction. The resulting differential EMGs were then filtered with a band-pass, second-order Butterworth filter (20–350 Hz cut-off frequencies) to remove movement artifacts and high-frequency noise. After that, RMS amplitude was computed over epochs corresponding to deciles of each of the two rowing phases, separately for subjects and rowing cadences and cycles. For each participant, a total of 1800 RMS values were obtained (2 rowing phases × 3 cadences × 10 deciles × 30 cycles). RMS values were then normalized with respect to the highest RMS amplitude. Lateral differences in EMG amplitude were first analyzed for rowing phases and cadences; RMS values were averaged across deciles and cycles. Finally, RMS values were averaged across cycles to test for whether participants activated their left and right back muscles differently within strokes.

Asymmetrical activation of low back muscles during rowing was further assessed in terms of regional changes in EMG amplitude. From the 22 differential EMGs obtained for each trunk side, we first automatically segmented the channels detecting greatest RMS amplitude (Vieira et al., 2010). From the longitudinal coordinates of segmented channels, we then computed the barycenter of the distribution of EMG amplitude along the cranial-caudal axis, for each subject, rowing cadence and deciles of each rowing phase separately. Specifically, the barycenter longitudinal coordinate was obtained by (a) multiplying the number of each row of segmented channels by their corresponding RMS amplitude; (b) summing up the products; (c) dividing the resulting value by the sum of RMS amplitude values. These barycenter coordinates indicate where, along the skin regions covered by the arrays, the amplitude of surface EMG was most strongly represented. We therefore considered such index to investigate whether, within the rowing cycles, distinct longitudinal sections of the back muscles in the left and right sides were activated equally strongly.

Prior to the computation of RMS amplitude, signals were subjected to a circumspect, visual inspection. An experienced evaluator screened EMGs for the presence of massive power line interference, motion artifact and electrode-skin, contact problems. Whenever any of these disturbances was observed, the EMG

detected by the corresponding channel was replaced by the signal obtained through linear interpolation of the neighboring EMGs.

Statistics

Parametric statistics were considered to test our hypothesis of symmetrical activation of the low back muscles during indoor rowing. After ensuring Gaussianity of our data (Lilliefors test) and homogeneity of variance (Levene's statistics), univariate analysis of variance (ANOVA) was applied to test for differences in the RMS amplitude of surface EMGs collected between the left and right trunk sides (3 rowing cadences × 2 trunk sides × 2 rowing phases). Rowing cycles were regarded as repeated measures. Side differences in the mean RMS amplitude and in the barycenter coordinates within strokes were evaluated with a similar approach. Finally, changes in the amount of trunk movement with stroke rate were investigated through one-way ANOVA. The duration of recovery and drive phases was compared with two-way ANOVA (2 phases × 3 cadences). Based on the effect size (40%) estimated from our data, 30 rowing cycles performed by six subjects ensured high (86%) statistical power (post-hoc power analysis; Faul et al., 2007).

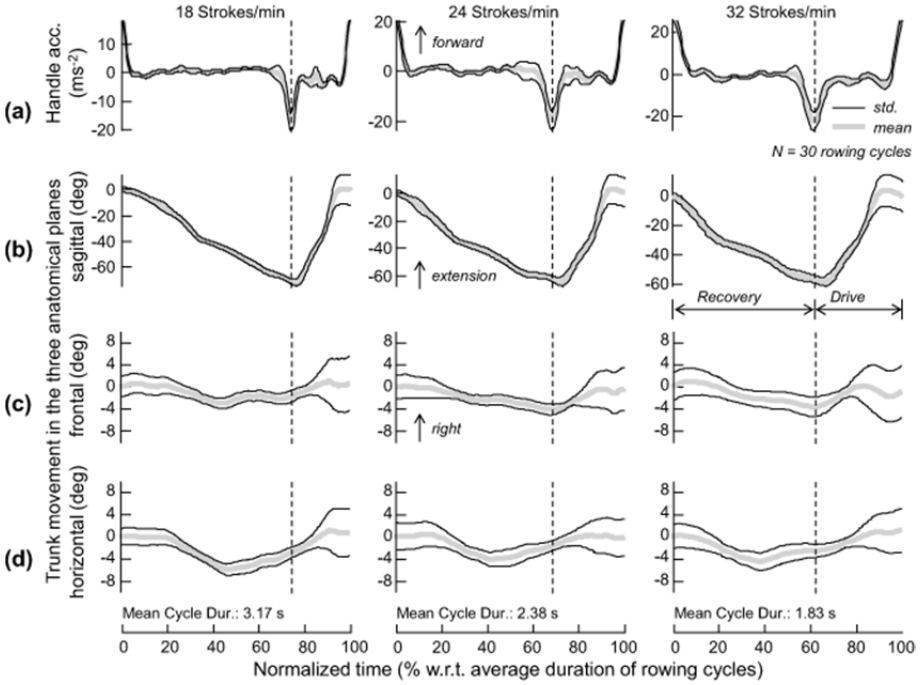
The intraclass correlation coefficient (ICC) was considered to assess the consistency of EMG amplitude and barycenter position across strokes and trials (i.e., before and after electrode repositioning). This coefficient indicates the proportion of the total variance that may be accounted for by the variability among subjects. High ICC values would indicate most of the variability observed is due to subjects rather than due to the rowing cycles and electrode position. Typically, ICC values ranging from 60% to 80% and from 80% to 100% are, respectively, regarded as “good” and “excellent” indicators of repeatability (Bartko, 1966). Given that ICC may assume negative values when the variability between subjects is comparable with the variability caused by other sources, we computed the ICC values as proposed by Rainoldi et al. (1999). ICC was calculated for the RMS amplitude and barycenter coordinate, separately for each of the 10 deciles of the drive phase.

Results

Trunk kinematics during indoor rowing

Results from a single, representative subject indicate a markedly small variation in handle acceleration throughout individual cycles (Fig. 2(a)). Except for the end of the drive phase, between-cycles variability in the trunk inclination in each of the three anatomical planes was similarly small; average standard deviation of trunk movement in all planes was smaller than 1° (see black traces in Fig. 2(b–d)). Close inspection of Fig. 2 suggests the peak-to-peak amplitude of trunk flexion-extension, lateral rotation, and lateral inclination did not depend on the stroke rate. Conversely, as expected, the mean duration of rowing cycles decreased dramatically with the increase of stroke rate. Such decrease was accounted for by the reduction of the time this participant spent in the recovery phase. In relation to the total duration of rowing cycles, the time spent in the recovery phase changed from 77% at 18 strokes/min to 69% at 24 strokes/min and to 61% at 32 strokes/min (Fig. 2).

Figure 2.



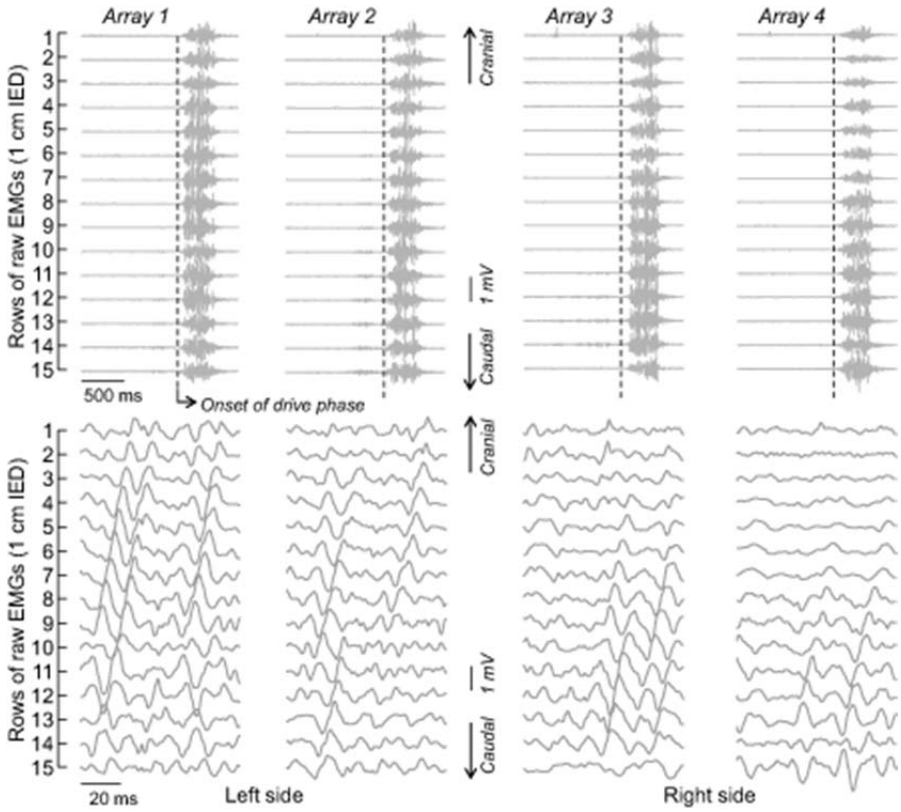
Trunk kinematics and handle acceleration. Profiles of handle acceleration are shown in (a) for each of the three rowing cadences (18, 24, and 32 strokes/min). Gray thick traces and black thin traces, respectively, indicate the mean and the standard deviation values, calculated across rowing cycles for a single participant. Positive values indicate forward direction. Trunk movements in the sagittal, frontal, and horizontal planes are depicted in (b, c, and d) rows, respectively. Positive values posit trunk extension and trunk inclination and rotation toward the right direction. Zero degrees correspond to the trunk inclination at the onset of recovery phase. Vertical dashed lines mark the catch instant, i.e., transition from recovery to drive phase. Average duration of cycles is reported for each rowing cadence in (d).

The duration of the rowing phases and the consistent variations in trunk and handle kinematics reported in Fig. 2 were equally well observed for all participants. On average, trunk movement occurred predominantly in flexion-extension direction (average range of motion values across rowing cadences; sagittal plane: 65.4 ± 9.4°; frontal plane: 2.6 ± 0.6°; horizontal plane: 2.9 ± 1.0°). Statistics did not indicate a main effect of rowing cadence on the amount of trunk movement in any direction (ANOVA; $P > 0.12$; $n = 18$; 3 cadences × 6 subjects). Duration of both rowing drive and recovery phases, however, decreased significantly with the increase in stroke rate (ANOVA main effect of stroke rate; $P < 0.001$; $n = 36$; 3 cadences × 6 subjects × 2 rowing phases). Mean duration of drive phase decreased from 0.83 ± 0.02 s to 0.79 ± 0.03 s and then to 0.73 ± 0.05 s when athletes increased their stroke rate, respectively, from 18 to 24 and then to 32 strokes/min. Average figures for the recovery phase (2.29 ± 0.11 s, 1.65 ± 0.07 s, and 1.14 ± 0.05 s) showed though a steeper decrease with stroke rate (ANOVA interaction effect; $P < 0.001$; $n = 36$). In relation to the duration of the full rowing cycle, the average duration of the recovery phase across subjects decreased from 72 ± 3% at 18 strokes/min to 67 ± 3% at 24 strokes/min and to 61 ± 4% at 32 strokes/min.

Quality of high-density surface EMGs during rowing

Visual inspection of surface EMGs revealed very few instances of low-quality recordings. Specifically, we observed the presence of power line interference and contact problems in less than 4 out of the 60 channels used to detect back muscles' activity. These issues were more frequently observed toward the last rowing trial, possibly because of subjects' sweating. In all cases, however, our recordings conveyed high-quality EMGs, similar to those shown in Fig. 3. Motor unit action potentials and their propagation are clearly evident through all the four array of electrodes used (see bottom panels in Fig. 3).

Figure 3.

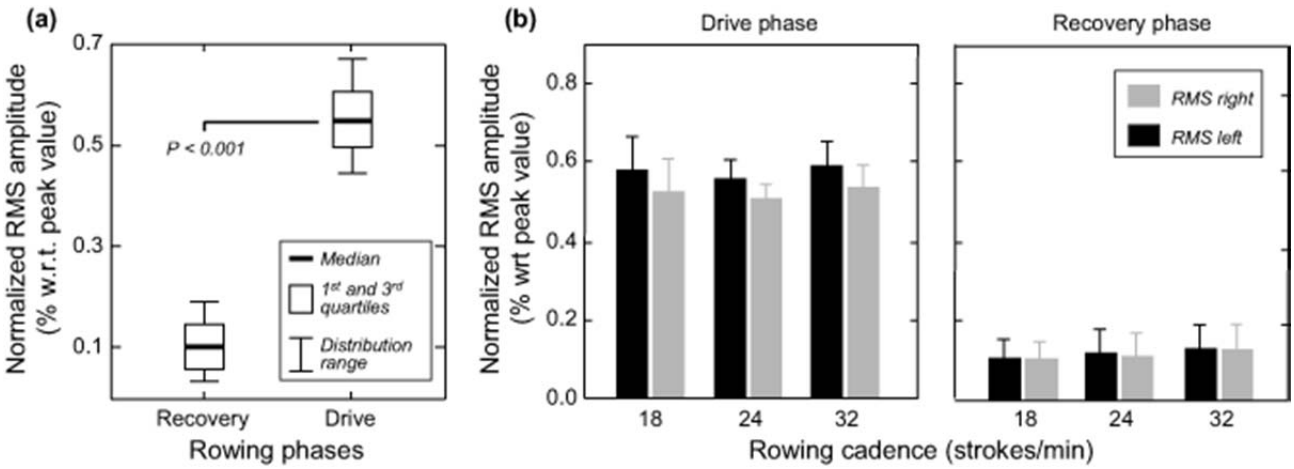


Activation of the back muscles for a single rowing cycle and participant. Raw surface, single-differential EMGs (gray traces) detected while a subject performed a single stroke at 18 strokes/min are depicted in the top row for each of the 60 channels separately. See Fig. 1 for anatomical specification on the position of arrays of electrodes in relation to the vertebral column. Vertical, dashed lines denote the onset of drive phase. Signals shown in the bottom row correspond to an expanded view (80 ms epoch) of the raw EMGs shown on top. Motor unit action potentials and their propagation are clearly appreciated in such magnified view.

Bilateral, regional changes in the degree and in the distribution of back muscles' activity

Surface EMGs revealed marked differences in the degree of low back muscles' activation between drive and recovery phases though not between left and right trunk sides when participants' data were averaged. Not surprisingly, average RMS amplitudes were about six times greater during drive than during recovery phase (Fig. 4(a)); ANOVA main effect; $P < 0.001$; $n = 72$; 3 cadences × 2 phases × 2 trunk sides × 6 subjects). Such difference did not depend on whether subjects rowed at fast or slow rates (Fig. 4(b)). Although the RMS amplitude of EMGs collected from the right trunk side was on average slightly (~8%) smaller than that of EMGs detected from the left side, this difference did not reach statistical significance (Fig. 4(b)). ANOVA results did not indicate a significant main effect of trunk side or interaction effect between trunk side and rowing cadences and phases on EMG amplitude ($P > 0.11$; $n = 72$). In virtue of the markedly greater amplitude values obtained during the drive phase, EMGs obtained for the recovery phase were disregarded from further analysis.

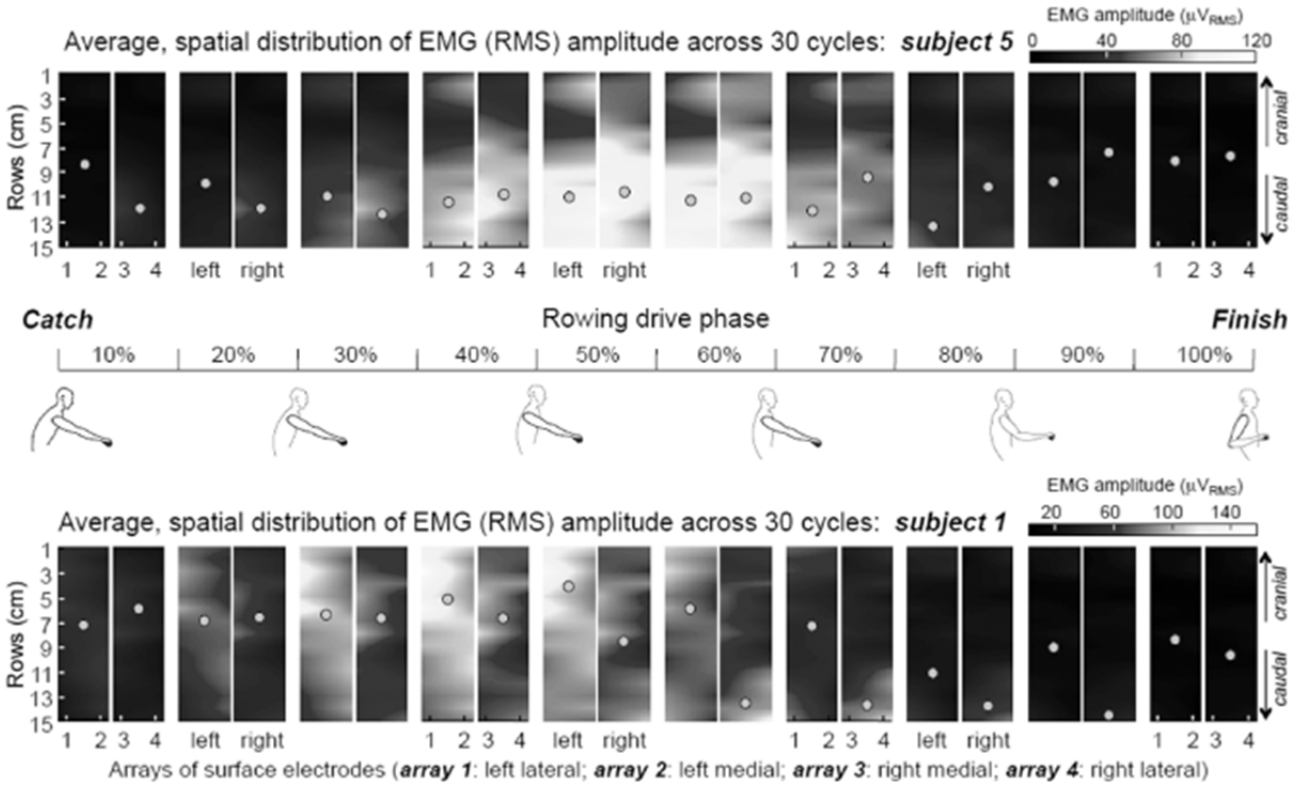
Figure 4.



Lateral differences in degree of low back muscles activation. (a) shows the distribution of RMS amplitude, calculated over the duration of recovery and drive phases and averaged over channels, trunk sides, rowing cycles, stroke rates, and subjects. Amplitude values were normalized with respect to the greatest amplitude value obtained across rowing cadences and cycles, separately for each subject and trunk side. (b) shows the same as in (a) for individual stroke rates and trunk sides (mean and standard deviations; gray bars: right side; black bars: left side). A significant main effect was revealed by ANOVA for the rowing phase ($P < 0.001$) though not for the trunk side when data was pooled across subjects. The nonparametric statistics considered to show the data in (a) indicate how much data distribution approached Gaussianity.

When considering participants individually, asymmetries emerged in EMG amplitude and in its proximo-distal distribution between the left and right low back muscles throughout the drive phase. Results from two participants are illustrated in Fig. 5 for a single stroke (24 strokes/min). The amplitude of surface EMGs detected from subject 5, for example, distributed similarly bilaterally from 40% to 60% of the drive, when EMG amplitudes reached the greatest values. The location and the degree of active regions, however, changed oppositely before and after reaching peak activation. Immediately after the catch, significantly greater EMGs were observed in the right side (ANOVA Fisher's least significant difference post-hoc; $P < 0.01$; $n = 60$; 3 cadences × 2 trunk sides × 10 percentiles of the drive phase). After peak activation and prior to the finish position, greater EMGs were detected in the left side and in the more caudal region ($P < 0.01$; $n = 60$). Participant 1, on the other hand, reached peak activation earlier, toward 30–50% of the drive phase, with EMGs in the left side being significantly greater and located more cranially than those in the right side (compare intensity maps and barycenter coordinates in Fig. 5 bottom panel; ANOVA; $P < 0.01$; $n = 60$).

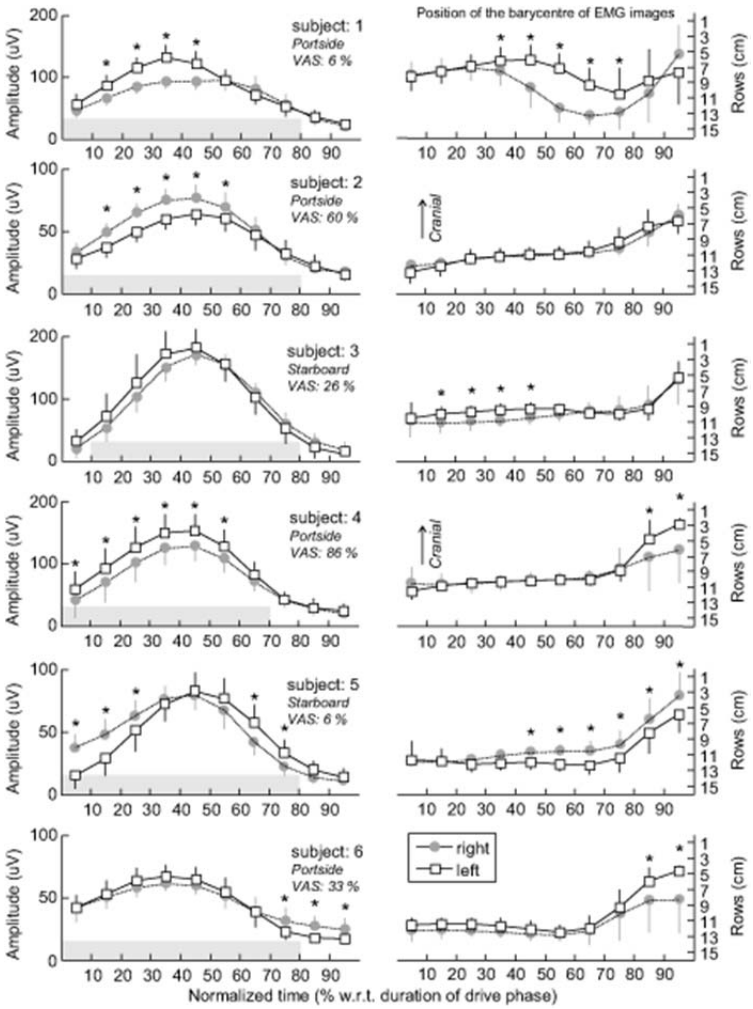
Figure 5.



Regional changes in the distribution of low back muscles activity. Mean RMS amplitudes calculated for each channel and array of electrodes are represented as intensity levels, with dark and light intensities denoting, respectively, low and high amplitude values. Such RMS images were obtained from EMGs confined within 10 consecutive deciles of the drive phase, separately for the left (arrays 1 and 2) and right (arrays 3 and 4) trunk sides. Amplitude values were interpolated by a factor of four, thus producing a smooth representation of spatial changes in RMS amplitude. See Fig. 1(a) for the anatomical correspondence between the number of rows and columns in the images and the position of electrodes. Circles within the images posit the longitudinal coordinates of the barycenter of each amplitude distribution over rows.

There was no common trend for the variation in the degree and location of back muscle activity between subjects. Figure 6 shows the amplitude and the barycenter proximo-distal coordinates for each rower; these values were averaged across rowing cycles and cadences within 10 deciles of the drive phase and analyzed separately for each subject. Subject 2 showed significantly greater EMG amplitude in the right side, without a corresponding difference in barycenter location. Conversely, subject 3 showed a significant though slight bilateral difference in the barycenter coordinate but not in EMG amplitude. At finish, when EMG amplitude was on average smaller than 50% of peak values, barycenter coordinates in the left side were located significantly more cranially than those in the right side for subjects 4 and 6. Lateral differences in EMG amplitude for these two subjects manifested at significantly different relative positions within the drive phase (from 10% to 60% for subject 4 and from 70% to 100% for subject 6). Finally, for all individuals tested, the asymmetries revealed by RMS amplitude and barycenter coordinate were not related to the small trunk movements occurring in either the frontal or horizontal plane.

Figure 6.



Regional variations in the degree of activation of the low back muscles. The mean amplitude and the cranio-caudal position of the barycenter of RMS amplitudes are reported for each of the 10 deciles within the drive phase (see Fig. 5). Amplitude values and barycenter coordinates were averaged across rowing cycles and stroke rates, separately for each athlete and trunk side (□: left side; : right side). Whiskers denote standard deviations. Light gray shades in the left plots indicate deciles of the drive phase when EMG amplitude was greater than two standard deviations of the baseline amplitude (27) defined as the EMG amplitude averaged over 500 ms from the onset of the recovery phase. Rowing side and pain intensity, quantified through the visual analog scale (VAS), are reported below subject number. Asterisks indicate significant side effect: $P < 0.01$.

Thickness of subcutaneous tissue

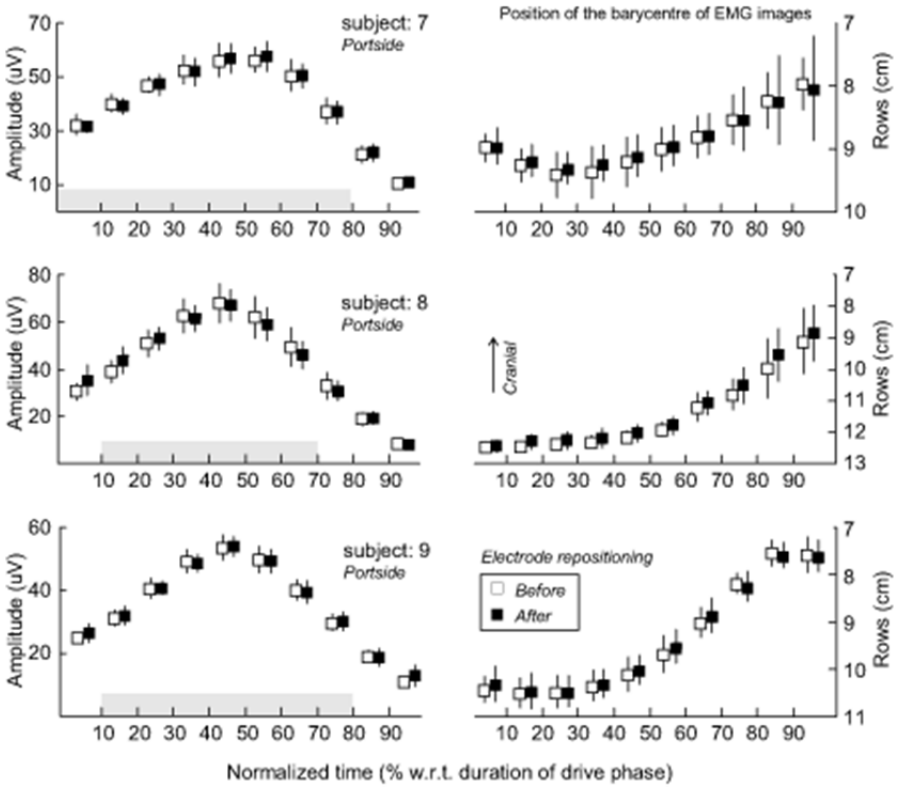
As quantified from ultrasound images, no statistically significant asymmetries were observed in the thickness of fat tissue. Specifically, the mean difference (0.1 mm; SD: 0.9 mm) between the values of fat thickness obtained for the left and right trunk side was not different from zero (Wilcoxon test; $P = 0.6$; $n = 12$; 6 subjects × 2 trunk sides).

Consistency of EMG descriptors among subjects

Changes in RMS amplitude and in the distribution of RMS amplitude along the lumbar spine within strokes were markedly consistent among subjects. Higher ICC values were observed in correspondence of deciles of the rowing cycle associated with significantly greater EMG amplitudes. Specifically, for deciles over which EMG amplitude was two times greater than the standard deviation of EMG amplitude averaged over 500 ms from the onset of the recovery phase (shaded rectangles in Fig. 7(a)), ICC values ranged from 87% to 98% ($n = 10$ deciles) and from 81% to 93% for the RMS and barycenter values, respectively. Within these

deciles, short-term repositioning errors in RMS amplitude and RMS distribution barycenter varied across sites from 0.8% to 6.0% (range of coefficient of variation values) and from 7.6% to 13.7%, respectively. Most strikingly, the relative changes in both RMS and barycenter values associated with electrode repositioning (Fig. 7) were dramatically smaller than those associated with trunk side (Fig. 6).

Figure 7.



Effect of electrode repositioning on the EMG amplitude distribution. The mean RMS amplitude and the mean barycenter coordinate along the longitudinal direction are reported for each of the 10 deciles within the drive phase. Amplitude and barycenter values were averaged across rowing cycles, separately for each of the three athletes and each of the two trials; before (□) and after (■) electrode repositioning (see Methods). Whiskers denote standard deviations. Light gray shades in the left plots indicate deciles of the drive phase when EMG amplitude was greater than two standard deviations of the baseline amplitude.

Discussion

This study investigated bilateral differences in activation of low back muscles during the highly demanding, rowing exercise. Movements of the lumbar spine were recorded with an inertial sensor (Fig. 2). Surface EMGs were sampled from multiple skin regions to ensure the relative movement between electrodes and muscles, the cross-talk from distant sources and the regional changes in activation would not bias our outcomes (Fig. 3). Key results posit different manifestations of low back asymmetry while six elite rowers performed on a rowing ergometer. Changes in EMG amplitude and in the location where greatest EMGs were detected along the lumbar segments varied differently between sides, without a clear predominance toward either right or left side between subjects (Figs. 5 and 6). These results suggest (a) the low back muscles seem to be activated asymmetrically during indoor rowing; (b) factors other than rowing side are presumably associated with low back asymmetries in sweep rowers; and (c) EMGs are sensitive to such uneven, bilateral activation of the low back muscles.

Trunk kinematics during rowing

The degree of trunk movement in the three anatomical planes was highly consistent both within and between subjects at catch and during almost the whole rowing cycle. Toward the finish position, however,

each individual moved their trunk to different extents and directions (black lines in Fig. 2). All tested rowers participated in international competitions, currently sustaining an average workload of 30 h per week. The relatively large kinematic variation at finish reported here was therefore not expected, given that a greater consistency of trunk flexion-extension has been documented for elite in comparison with collegiate rowers (McGregor et al., 2004, 2005). One possible reason for this could be the procedure we selected to position our inertial sensor. In an attempt to detect the trunk motion as much as possible during strokes, we positioned an inertial sensor at L3 with a large elasticized, Velcro strap. This strap covered a remarkably large longitudinal, spinal region (Fig. 1). It is therefore possible that the Velcro strap loosened slightly with trunk extension when rowers approached the finish position. In such case, the large variability of trunk motion observed at finish was likely caused by the relative movement between the sensor and the trunk; at finish, for example, the chest absorbs marked impacts because of vigorous shoulder extension and elbow flexion.

Of crucial importance to our study is the amount of lateral movement of the lumbar spine in relation to flexion-extension movement during rowing. Figures for the amplitude of lumbar lateral rotation and inclination during indoor rowing were not found in the literature. Conversely, the flexion-extension amplitude of rowers' lower trunk seems well documented. Different accounts on elite rowers have reported different ranges of motion for the lumbar flexion-extension, from figures as small as 15–20° (Caldwell et al., 2003; Pollock et al., 2009) to large ranges of motion as ∼40° (McGregor et al., 2005). Regardless of whether differences between studies could have been due to methodological issues related to detection of trunk motion, our values for the range of lumbar motion in the sagittal plane are markedly greater than these previous estimates. Interestingly, our average estimation of trunk full flexion-extension is similar to the lumped lumbo-pelvic motion reported by Pollock et al. (2009). Very likely, kinematic results reported in our study reflect the motion of pelvic and lumbar segments. This would further explain the trunk angle changes observed in the transition from mid-recovery to catch (Fig. 2(b)), when trunk is supposed to remain steady while hip flexion leads into the catch (Torres-Moreno et al., 2000; Soper & Hume, 2004; McGregor et al., 2005). In spite of such intersegmental contribution to changes in the orientation of our inertial sensor, rotation and lateral inclination during strokes were dramatically smaller than flexion-extension movement. These small movements outside the sagittal plane were not associated with rowing side.

Differences in activation between recovery and drive phases

Notwithstanding the bilateral differences in activation, as expected, our subjects activated their left and right back muscles predominantly during the rowing drive phase (Fig. 3). This observation is well in agreement with previous reports on elite athletes during indoor rowing. Turpin et al. (2011), for example, studied an extensive set of muscles potentially involved in the rowing gesture. Key synergists were mainly located in the leg and trunk segments and were activated during the drive phase (Turpin et al., 2011). Specific indications from surface EMG further show the erector spinae activity peaks from 40% to 60% of the drive phase (Caldwell et al., 2003; Pollock et al., 2009), with the thoracic segment of the back muscles being activated earlier and for a longer duration than the lumbar segment. Except for subject 1 (a particular case we discuss in the next section), all rowers tested in our study showed peaks of activity within such range (Fig. 6). Corroborating previous findings (Pollock et al., 2009), our rowers kept a relatively high level of activation for a relatively long period (70–80% of drive). For most subjects, activity at the catch onset was not as small as at the finish. This modest level of activation is expected, in particular for the thoracic segment (Pollock et al., 2009; Turpin et al., 2011), given that rowers must sustain their trunk in a flexed position prior to the catch. Therefore, any left-right asymmetries occurring during indoor rowing seem more critical during the drive than recovery phase, when back muscle activation reaches its greatest level.

The level of back muscles' activity is not however the sole variable of interest; asymmetries may manifest in terms of differences in activity as well as in the location of activity along the spine. From the arrays of electrodes used in this study, we were able to quantify the degree of back muscle activity as well as the back region showing greatest levels of activity throughout strokes. Proximo-distal regions showing greatest

activity in the spine were estimated through the longitudinal coordinate of the barycenter of the RMS amplitude distribution (Fig. 5; Vieira et al., 2010). Our barycenter analysis revealed a consistent coordination of trunk extensor muscles across subjects (Fig. 6). Early in the drive phase, the barycenter was located distally in the grids, suggesting the back muscles in the lower lumbar spine were predominantly active. With the progression of the drive phase, the barycenter shifted proximally, indicating the contribution of back muscles in the thoracic and higher lumbar spine to completion of the rowing stroke increased progressively. Such a distal to proximal shift of activity throughout strokes is in agreement with previous findings; muscles in the upper trunk regions are activated relatively later and for a longer duration than those in lower trunk regions within the drive phase (Pollock et al., 2009; Turpin et al., 2011). The spatiotemporal redistribution of activity within trunk extensors has been suggest as an effective strategy to compensate for the shear forces resulting from the trunk intersegmental movements occurring during the rowing drive phase (Pollock et al., 2009). The location along the spine where back muscles were most strongly loaded during the drive phase posits therefore a relevant set of information for the study of asymmetries during rowing.

What are the possible origins of asymmetric, back muscle activation during indoor rowing?

Side differences in back muscle activation have been observed even for tasks primarily demanding extension efforts. Wolf et al. (1997) reported asymmetries in the amplitude of EMG envelopes collected bilaterally from sacrospinalis muscles during voluntary, forward trunk movements. During sustained, submaximal (60% of maximal effort) trunk extensions, Mannion et al. (1997) observed the changes in EMG spectral descriptors in the left side were more strongly correlated with endurance time than those in the right side. These side differences were conceived as a potential consequence of trunk torsional torque, possibly related to side dominance (Mannion et al., 1997; Wolf et al., 1997). Indeed, back muscle asymmetries have also been documented for electrically elicited contractions (Merletti et al., 1994). During this condition, side differences could not result from asymmetric trunk loading; they were rather suggested to reflect adaptation mechanisms likely resulting from greater use of muscles in the dominant side (Merletti et al., 1994).

In spite of the asymmetries inherently imposed by sweep rowing to the trunk muscles, side differences observed during indoor rowing were unlikely related to rowing side. When on water, sweep rowers rotate their trunk toward the oar direction in preparation to the catch and, then, in the opposite direction during the drive. This intrinsic, asymmetric loading of the back muscles in sweep rowers could possibly lead to differential adaptations of muscles located in different proximo-distal and left and right spinal segments. Although imaging analysis revealed similar cross-sectional areas for the left and right back muscles in elite rowers (McGregor et al., 2002), asymmetric neural adaptation in sweep rowers have been suggested from surface EMG (Parkin et al., 2001; Rosatelli et al., 2008). The point here is whether the left and right differences in EMG amplitude shown in Fig. 6 were predominantly related to rowing side. If so, we would expect them to manifest equally for athletes rowing at the same side, i.e., starboard or portside rowers. Unfortunately, studies quantifying back muscle activation in rowers from surface EMGs were either not focused on left-right asymmetries (Wajswelner et al., 2000; Caldwell et al., 2003; Pollock et al., 2009; Turpin et al., 2011) or did not assess asymmetric activation during the rowing stroke (Parkin et al., 2001; Rosatelli et al., 2008). Although comparison with previous findings is therefore not possible, our results show different asymmetries in EMG amplitude within portside and starboard rowers (Fig. 6). These differences between subjects presumably suggest factors other than rowing side were more strongly associated with side differences in back muscle activation.

Low back pain and spine deformities could have potentially contributed to the uneven, bilateral activation of back muscles during the rowing stroke. Specifically, in relation to pain and asymmetries, subjects reporting chronic low back pain seem more likely to show asymmetric activation of back muscles than controls (Newcomer et al., 2002). Interestingly, among our subjects, those exhibiting greater degrees of asymmetry were also those reporting higher scores for back pain episodes. Two portside rowers, subjects 2 and 4, who presented significantly greater activation of right and left back muscles, respectively, were also

those reporting greater pain intensities (Fig. 6). Subject 1, on the other hand, reported negligible episodes of back pain but exhibited a peculiar pattern of asymmetric activation; activation in the left side was significantly greater and located more cranially than activation in the right side (Figs. 5 and 6). Such greater, cranial EMG amplitude observed for the left back muscles could be associated with the markedly large scoliotic, left convex curvature (Cobb angle greater than 15°) reported by this subject. Previous evidence on the distribution of back muscle activity posits greater activation of muscle segments located at the convex side and in correspondence to the apex of the scoliotic curve (Cheung et al., 2005). Considering this subject was a gold medalist in the World and European Rowing Championships in 2012 and 2013, respectively, the functional relevance of his asymmetry deserves, however, further investigation. Subject 5 also did not report episodes of low back pain though he showed significantly greater activation of left and right back muscles, respectively, at the first and last deciles of the drive phase. Differently from the other participants, this subject has not changed rowing side since he started rowing competitively. The asymmetric pattern exhibited by this subject is possibly predominantly caused by side differences related to training demands, i.e., greater contralateral activation of back muscles is expected for sweep rowers at the onset of the drive phase. The relative contribution of different anatomical and physiological factors to the asymmetries observed remains, however, to be investigated.

Some considerations on electrode positioning, sample size, and implications of results

Multiple causes typically account for the changes in the amplitude of back muscles' EMGs. First, variations in EMG amplitude are not unambiguously related to variations in the degree of muscle activation; it is well established that pairs of electrodes detect negligible potentials if positioned symmetrically in relation to the muscle innervation zone (Merletti et al., 1994; Farina et al., 2003). During dynamic tasks (e.g., indoor rowing; Fig. 2), when relative movements between electrodes and muscle fibers are likely to occur, changes in EMG amplitude are potentially caused by shifts in the location of innervation zones (Farina et al., 2003). Such anatomical consideration is further aggravated by the differential arrangement of muscle fascicles across and along the spine (Bustami, 1986) and the markedly high interindividual variation in fascicles' architecture (DeFoa et al., 1989). Second, any possible association between specific back muscles and the regions of activity identified from surface EMGs (e.g., Fig. 5) must be made on circumspect grounds. Despite existing recommendations for electrode positioning (Barbero et al., 2012), it is arguable whether surface EMGs detected in a specific back location unequivocally samples from the target muscle (Stokes et al., 2003). Finally, it has been shown that subtle changes in lumbar curvature lead to a redistribution of activity within and between the back muscles (Claus et al., 2009). Considering there is a varying degree of intersegmental motion along the spine during rowing (Pollock et al., 2009), different proximo-distal segments of the back muscles might be loaded, and thus activated, unevenly. Collectively, the three issues highlighted here – architectural changes, cross-talk, and inhomogeneous activation – could lead to spurious indication on bilateral differences in back muscle activation during rowing.

Notwithstanding these potential confounding sources, it should be noted that our study was focused on identifying lateral variations in EMG amplitude, possibly leading to or resulting from asymmetrical loading of the low back. In particular, arrays of electrodes covered a large longitudinal and transverse region on both trunk sides. The relatively large region of the back muscles covered by our electrode grids possibly explains the high consistency (ICC values ranging from 81% to 98%) observed for EMG descriptors among subjects. More specifically, such a high consistency indicates the EMG asymmetries reported for the six elite rowers tested in this study were unlikely caused by systematic issues related to electrode positioning. Any eventual regional change in back muscle activity occurring during indoor rowing in either side caused by anatomical factors or by a genuine drive of activation to different muscle regions, was expected to be represented in our arrays of electrodes (Farina et al., 2003). As these segmental changes did not manifest equally in both sides (Figs. 5 and 6), and considering there was no difference in the thickness of subcutaneous tissue between right and left trunk side (see Results), we therefore presume they are indicative of low back asymmetries during indoor rowing.

A subset of rowers showing common bilateral changes could have potentially emerged had we tested a larger sample. However, the fact that six rowers showed different trends in bilateral low back activation does not mean our results lack relevance. In their series of case studies, for example, Ikeda & McGill (2012) reported a spectrum of painful intolerances in the low back emerging from provocative testing. These authors further observed that different maneuvers were effective to reduce pain in each of the four subjects tested. In the specific case of sweep rowers performing on an indoor machine, an assortment of anatomical and physiological factors could be associated with asymmetries: differential muscle adaptation resulting from side dominance or rowing side, uneven distribution of hip extension forces, abnormalities in spine curvature, presence of pain and fatigue, among others. Although we value the possibility of recruiting homogeneous samples in future studies, our data collected from a small number of sweep rowers highlight the potentiality of distinguishing elite rowers based on how they activate their back muscles bilaterally during indoor rowing.

Perspectives

Key methodological and applied perspectives prompt from the present study. Even during indoor rowing, that is, even in absence of boat stabilization demands imposed by on-water rowing, sweep rowers seem to activate their back muscles asymmetrically. Most interestingly, we show these asymmetries manifested (a) as side differences both in the degree and in the distribution of EMG amplitude within muscles; and (b) differently for each of the six, elite rowers tested. These findings indicate that surface EMGs recorded with arrays of electrodes posit a promising tool for the monitoring of back muscles' asymmetries during the highly demanding and dynamic, rowing exercise. Considering the sensitivity of EMGs to fatigue in the back muscles (Roy et al., 1990; Merletti et al., 1994; Mannion et al., 1997) and to asymmetries during rowing (Fig. 6), surface EMGs detected bilaterally could thus provide an additional means of identifying and treating rowers predisposed to low back pain (O'Sullivan et al., 2003; Smoljanovic et al., 2009). Moreover, EMGs could integrate the valuable set of kinematic, feedback information (Baudouin & Hawkins, 2002; Smith & Loschner, 2002) assisting rowers and coaches to improve performance. Although it is not possible to ascertain whether the asymmetries observed here would occur during on-water rowing, the significance of our results is supported by the representative fraction of training volume both sweep rowers and scullers spend indoor; ergometers are indeed used for the selection of national teams, for the conditioning of rowers, especially during winter, and in the world championships for indoor rowing (CRASH-B).

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